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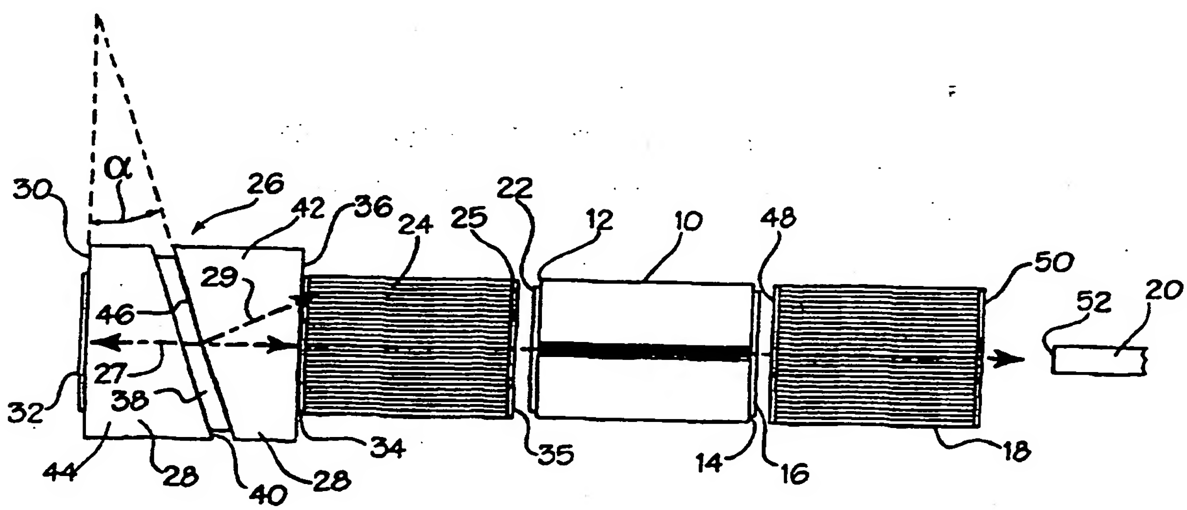

(57) Abstract

A miniature, external cavity, filter-locked laser has a semiconductor optical amplifier, such as a diode laser, and a monolithic prism assembly positioned in the external res nant cavity. The monolithic prism assembly includes a transparent substrate carrying a thin film Fabry-Perot interference filter which is tilted, that is, oriented not normal to the path of the travel of the laser light in the external cavity. Such optical devices can be economically mass produced in advantageously small size, having reproducible spectral performance properties held within tight tolerances. Significantly advantageous applications include dense wavelength division multiplexing systems requiring tightly spaced wavelength subranges for each of the multiple channels. High wavelength stability against temperature and humidity changes, etc., can be achieved.

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EXTERNAL CAVITY SEMICONDUCTOR LASER WITH MONOLITHIC PRISM ASSEMBLY

FIELD OF THE INVENTION

The present invention is directed to optical devices having an external cavity semiconductor laser, such as an external cavity diode laser, in which an external optical cavity extends between one facet of an edge-emitting semiconductor optical amplifier and an external reflector. More particularly, the present invention is directed to external cavity semiconductor optical amplifiers having stabilized emission wavelengths.

BACKGROUND

External cavity semiconductor lasers are known and have numerous uses and applications, including fiber-optic communications. In external cavity diode lasers which are typical of such optical devices, an optical cavity extends between one facet of an edge-emitting semiconductor diode laser and an external high reflector. A second facet of the edge-emitting semiconductor laser, between the high reflector and the first facet, typically carries an anti-reflection coating to allow light to escape the laser chip with minimum reflection.

Semiconductor diode lasers have been used extensively as transmitters for fiber-optic communications. In one common and low cost implementation, edges of two opposing end facets of the laser chip are cleaved to form resonant reflective surfaces and provide the feedback necessary for laser operation. Such Fabry-Perot (FP) lasers typically emit in multiple longitudinal modes and have large output bandwidths, for example, 3 nm to 10 nm. In another common implementation with slightly increased complexity, a Bragg grating is etched in the active region of the Fabry-Perot laser cavity to form a distributed

feedback laser (DFB). Distributed feedback lasers have the advantage of single longitudinal mode emission which provides very narrow bandwidths typically, for example, less than 0.01 nm. In a third application, the distributed Bragg reflector (DBR) laser substitutes a wavelength-selective Bragg grating for one of the cleaved facets of the Fabry-Perot laser. The wavelength-selective Bragg grating has the effect of producing a laser with single longitudinal mode output.

Application of these and other diode lasers has been impeded due to inadequate stability and accuracy in the particular wavelengths generated. In particular, for example, such difficulties have been experienced in the application of diode lasers in Dense Wavelength Division Multiplexing (DWDM). In this advanced fiber-optic communication technology, many closely spaced wavelengths or channels are transmitted simultaneously down a single fiber or fiber bundle. Typical spacing of channels in DWDM systems can range from 5 nm to as little as 1 nm or less between channels. To accomplish effective DWDM systems, stable and accurate transmitters of predetermined wavelengths are needed for each individual channel. In addition, stable and accurate wavelength-selective receivers are needed to selectively remove or receive the individual channel wavelengths with low or no cross talk from other channels. For a DWDM system to operate efficiently, therefore, the transmitter and receiver device for a given channel must be tuned with great accuracy to the same wavelength band.

Unfortunately, the wavelength band emitted by presently known semiconductor diode lasers, including the above mentioned FP lasers, DFB lasers and DBR lasers, vary to an unacceptably large degree with temperature and other factors. Center wavelength temperature dependence of an FP laser, for example, is typically as much 0.4 nm per degree centigrade change in operating temperature at room temperature. The comparable variance for DFB lasers is typically as much as 0.1 nm per degree centigrade. Presently known

semiconductor diode lasers also suffer the disadvantage of poor manufacturing repeatability. That is. an intended or specified emission wavelength is not achieved with adequate accuracy when such lasers are produced in large commercial quantities. These deficiencies render present semiconductor diode lasers difficult and costly to implement into demanding applications such as DWDM systems, and in many cases entirely unsuitable.

It is known that the temperature dependence of an individual laser can be mitigated by controlling the temperature of the laser to within an extremely small temperature range using, for example, thermoelectric coolers with closed loop feedback from a temperature sensor. Such controls are complex and costly. The even more difficult problem of controlling lot-to-lot wavelength variation in commercial manufacturing of presently known semiconductor diode lasers, which can be as great as ± 5 nm and even ± 10 nm. has been partially addressed by culling through production batches for lasers having the desired wavelength. This technique of wavelength testing of individual lasers has significant adverse impact on manufacturing yield, with correspondingly increased costs and complexity.

It has also been proposed to use an alternative type of semiconductor diode laser, specifically, external cavity tunable lasers. External cavity tunable lasers are suggested, for example, in <u>Widely Tunable External Cavity Diode Lasers</u>, Day et al. SPIE, Vol. 2378, P. 35-41. In the diode laser devices suggested by Day et al. an anti-reflective coating is placed on one facet of a diode laser chip. The emitted light is captured within a collimating lens, and a diffraction grating is used to select or tune the wavelength of the laser. Laser action occurs, generally, provided that the grating is selecting a wavelength within the diode's spectral gain region. A diode laser device employing a diffraction grating disposed in an external cavity also is suggested in U.S. patent 5,172,390 to Mooradian. Unfortunately, diffraction gratings disposed within the external cavity of a diode laser causes a significant

increase in the overall size or bulk of the device. The diffraction grating and the complexity of the required grating alignment system can also significantly increase the cost of the device. As to the size or bulk of the device, the cavity length for a diode laser having a diffraction grating disposed in an external resonant cavity, in accordance with known devices, is typically from 25 mm to over 100 mm, in contrast to the much smaller 1 mm size or smaller of FP lasers and DFB lasers discussed above. The diffraction grating and grating mount also have been found to exhibit temperature dependence. Since the diffraction grating sets the wavelength of the laser, such temperature dependence of the grating and grating mount cause unwanted instability in the emitted wavelength of the laser. In addition, long term wavelength drift problems have been experienced due, it is believed, to the mechanical complexity of the diffraction grating and grating mount aspects of such devices.

It is an object of the present invention to provide semiconductor laser devices having good wavelength stability and accuracy. In particular, it is an object to provide such devices having acceptable manufacturing costs, complexity, and size or bulk characteristics. Additional objects of the invention will be apparent from the following disclosure and from the detailed description of certain preferred embodiments.

SUMMARY

In accordance with a first aspect, an external cavity laser is provided, having an optical amplifier optically coupled to an external resonant cavity, with a monolithic prism assembly in the external resonant cavity. In accordance with certain preferred embodiments, the optical amplifier is a semiconductor optical amplifier, such as those used in diode lasers, e.g., those formed of InGaAsP. Other suitable gain elements include, for example, erbium doped silica, germania or other optical material formed as fiber, etc. In

certain embodiments the optical amplifier is a direct bandgap optical emitter. The monolithic prism assembly comprises a transparent substrate, that is, a substrate which is substantially optically transparent to the laser light, and incorporates a Fabry-Perot interference filter comprising multiple thin film reflectors sandwiching at least one thin film cavity between them.. The thin film Fabry-Perot interference filter is disposed in the path of travel of the laser light in the external cavity. More specifically, it is oriented at a slight angle to a transverse plane. That is, it is carried on a surface of the transparent substrate (an internal or external surface, as discussed below) which is disposed at a non-zero angle to a transverse plane. As used here, a "transverse plane" is an imaginary plane normal or orthogonal to the path of laser light in the external cavity. Correspondingly, a transverse surface of the transparent substrate is one which lies in (or approximately in) a transverse plane. Thus, the thin film Fabry-Perot interference filter is in a non-transverse plane; it is not normal to the path of travel of the laser light passing through it. Rather, it is at an acute angle, typically less than 45° and more than 0°, preferably about 1° to 5°, more preferably about 1° to 2° to a transverse plane.

The thin film Fabry-Perot interference filter, in accordance with one aspect, is a stable, narrowband interference filter provided as a coating on a surface of the transparent optical substrate of the monolithic prism assembly. While the interference filter preferably has at least one thin film cavity layer sandwiched between thin film reflector layers, more preferably, it is a multi-cavity filter of two to five cavities, most preferably having two or three cavities. Each such cavity has an optical thickness (calculated as its actual physical thickness times the refractive index of the cavity material) equal to an even number of quarter wavelengths or QWOTs. The wavelength referred to is typically about the center of the wavelength band of laser light to be transmitted through the filter. Each cavity layer preferably is formed of one to three dielectric films, each such film having an optical

thickness equal to an even number of quarter wavelengths preferably totaling 1 to 15. more preferably 5 to 10 half wavelengths optical thickness for each such dielectric film. The reflector layers sandwiching a cavity layer between them each preferably is formed of quarter wavelength optical thickness films, as described further below. Most preferably, the filter is a multi-cavity thin film Fabry-Perot narrowband interference filter wherein the individual reflector cavities film structures are coherently coupled to each other using a quarterwave thickness optical coupling layer. The use of a multiple cavity Fabry-Perot interference filter in the monolithic prism assembly yields a filter with increased slope of the spectral skirts, along with a wider transmission zone, as compared to a single cavity filter. Both of these effects yield highly beneficial improvements in the performance characteristics of the external cavity lasers disclosed here in comparison with prior known filtering devices, such as etalons and diffraction gratings, as discussed further below.

It will be further understood from the discussion below, that the monolithic prism assembly need not provide any light diffraction function in the classic sense of a prism. Light from the optical emitter is acted upon, such that in-band light is transmitted and out-of-band light is reflected away. Thus, in-band light is separated from out-of-band light. The monolithic prism assembly could also be referred to as a filter monolith, again meaning a transparent substrate assembly incorporating a thin film Fabry-Perot interference filter comprising at least one thin film cavity sandwiched between thin film reflectors.

The monolithic prism assembly in accordance with certain preferred embodiments carries a reflective coating, preferably a high reflection coating, on a transverse surface defining one end of the external resonant cavity of the optical amplifier, and the aforesaid Fabry-Perot interference filter is carried on a second surface which is spaced from, and at an acute angle to the first surface. Optical devices in accordance with this aspect advantageously comprise an external cavity, edge emitting semiconductor diode laser

having an anti-reflection coating on a first emitter facet optically coupled to the external resonant cavity. An output coupler reflective coating is provided on a second emitter facet of the diode laser. The monolithic prism assembly is positioned in the external resonant cavity, comprising a transparent optical substrate carrying a cavity-reflective coating on an external surface to define one end of the external resonant cavity. A thin film Fabry-Perot interference filter is provided on a second surface of the optical substrate, being positioned within the external resonant cavity between the reflective coating and the first emitter facet. One or more collimating means, such as gradient index lenses or bulk lenses, etc., also are positioned in the external resonant cavity, e.g., for focussing light between the Fabry-Perot interference filter and the first emitter facet of the diode laser. Isolators can be used outside the cavity in the usual way.

Those who are skilled in the art, or knowledgeable in this area of technology, will recognize that the optical devices disclosed here are a significant technological advance. External cavity lasers employing semiconductor optical amplifiers in accordance with this disclosure can be produced with accurate and reproducible emission wavelengths, excellent temperature stability, and excellent resistance to wavelength drift. Moreover, it is highly significant that such lasers, especially in accordance with preferred embodiments, can be produced in miniature size and in large commercial quantities, having manufacturing costs comparable to known FP lasers, DFB lasers or DBR lasers. As discussed below, preferred embodiments of the laser devices disclosed here may be referred to as filter-locked lasers for their use of thin film Fabry-Perot interference filters in the external laser cavity to stabilize or lock the emitted wavelength or band. Preferred embodiments of the lasers disclosed here, and optical devices incorporating them, can be reproducibly manufactured in commercial quantities with emission wavelength held to within $\pm$ 0.1 nm, and with temperature dependence of 0.005 nm/°C or less, preferably .001 nm or less. Long term

wavelength drift can be held to less than ± 0.1 nm. Moreover, the monolithic prism assembly incorporating the thin film Fabry-Perot interference filter enables overall cavity length of the diode laser to be less than 5 mm in certain preferred embodiments. Those skilled in the art will recognize that these packaging and performance characteristics render preferred embodiments of the lasers disclosed here, and optical devices incorporating them, suitable and commercially practical for applications such as, most notably, dense wavelength division multiplexing fiber-optic communication systems. As discussed above, previously known diode lasers, such as those incorporating diffraction gratings or the like for wavelength control, were too complex, bulky, unreliable and/or costly to satisfy the exacting requirements of such applications.

Additional aspects and advantages of the present invention will become apparent or more readily understood from the following detailed description of certain preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

Certain preferred embodiments of the invention are discussed below with reference to the accompanying drawings in which:

Fig. 1 is a schematic illustration of a first preferred embodiment of an optical device incorporating an external cavity laser in accordance with the foregoing disclosure;

Fig. 2 is a schematic illustration of an external cavity laser in accordance with a second preferred embodiment;

Figs. 3 - 5 are schematic illustrations of the thin film Fabry-Perot interference filter of the monolithic prism assembly suitable to be employed in the semiconductor optical amplifiers of Figs. 1 and 2;

Fig. 6 is a graph showing the theoretical performance of a high quality three-cavity Fabry-Perot interference filter in accordance with Figs. 3 - 5. along with the corresponding performance of comparable one and two-cavity thin film Fabry-Perot interference filters;

Fig. 7 is a schematic illustration of an optical device comprising an external cavity laser in accordance with another preferred embodiment; and

Fig. 8 is a schematic illustration of a dense wavelength division multiplexing device incorporating a number of external cavity lasers in accordance with the present invention.

It should be understood that the optical devices illustrated in the drawings are not necessarily to scale, either in their various dimensions or angular relationships. It will be well within the ability of those skilled in the art, with the aid of the foregoing disclosure and the following detailed description of preferred embodiments, to select suitable dimensions and angular relationships for such devices intended for a particular application.

DETAILED DESCRIPTION OF CERTAIN PREFERRED EMBODIMENTS

Those who are skilled in this area of technology will recognize from the above discussion that the external cavity lasers disclosed here have numerous applications, including use in fiber-optic telecommunications systems. especially in systems employing dense wavelength division multiplexing wherein extremely narrow and precisely controlled transmission wavelengths are required. Additional applications include. for example, use in test equipment and the like, as well as laboratory instrumentation.

In contrast to previously known laser devices. such as FP lasers. DFB lasers and DBR lasers, in the devices disclosed here a thin film Fabry-Perot interference filter carried on a transparent substrate is used in an external laser cavity to lock the emitted wavelength or band of the external cavity laser within a narrow gain region. The laser can even be limited to a single emission mode by employing a suitable thin film Fabry-Perot narrowband

interference filter. Thus, the lasers disclosed and discussed here can be said to be filter-locked. Miniature (e.g., having an external resonant cavity of overall length, including the monolithic prism assembly, of less than 5 nm) thin film filter-locked external cavity lasers, or "FL lasers" as they will be referred to in some instances below, have especially advantageous application in DWDM fiber optic telecommunication systems. Precise and stable wavelength laser emitters are called for in such applications, so that closely spaced transmission channels are reliably separate and distinct. Those skilled in the art will recognize, that there are various other applications for the FL lasers disclosed here, especially applications calling for a stable and accurate narrowband laser source.

In the FL laser schematically illustrated in Fig. 1, an external cavity diode laser assembly is seen to include a laser diode chip 10 having a first emitter facet 12 and a second, opposite emitter facet 14. Emitter facet 14 carries a coating, specifically, an output coupler mirror, that is, an output coupler reflective coating 16. Light emitted through coating 16 is received into collimating lens 18 which preferably is a gradient index lens or the like. Collimated light from gradient index lens 18 is passed to fiber-optic pigtail 20, whereby it enters a fiber-optic communication system. Grin lens 18 could optionally be deleted in favor of a butt coupling between emitter facet 14 (with anti-reflective coating 16) and pigtail 20. Additionally, an isolator can be employed outside the cavity following a gradient index lens or other collimating lens, passing light to pigtail 20. Isolators are generally well known and their use and the use of other optional components in the FL lasers disclosed here will be apparent to those skilled in the art in view of the present disclosure. Emitter facet 12 carries coating 22, preferably an anti-reflective coating. Light passing through anti-reflective coating 22 is received and collimated by a second collimating means 24 which, again, preferably is a gradient index lens or the like. Light is passed from collimating means 24 into a monolithic prism assembly 26 comprising a transparent optical substrate 28.

Substrate 28 preferably is optical glass, such as BK7 or B270, both available from Schott Glaswerke (Mainz, Germany), or the like. Outside surface 30 of substrate 28 carries high reflector end mirror 32, such that the external cavity of the diode laser is defined between output coupler mirror 16 and high reflector end mirror 32. Preferably, anti-reflective coating 34 is carried on exterior surface 36 of substrate 28 to facilitate passing of collimated light from lens means 24 into the monolithic prism assembly 26.

The prism assembly further comprises thin film Fabry-Perot interference filter 38 on internal surface 40 of substrate 28. An "internal surface" as that term is used here, most typically is a surface-to-surface contact interface between two parts or pieces of transparent substrate which have been cemented or otherwise integrated to each other to form the monolithic prism assembly. An optical coating on an internal surface, for example the Fabry-Perot interference filter 38, is advantageously protected and stabilized by the bonded pieces of the substrate between which it is sandwiched. In that regard, it should be recognized that the gap shown between first piece 42 of substrate 28 and second piece 44 is highly exaggerated in Fig. 1 for purposes of illustration. It should also be recognized that Fabry-Perot interference filter 38 could be formed on interfacial surface 46 of part 42, as well as on interfacial surface 40 of part 44. An external surface, correspondingly, is a surface of the substrate which does not form a surface-to-surface contact interface with another part or portion of the substrate. It may, therefore, be exposed to atmosphere or in abutment with another optical element, such as a collimating means, mounting structure or the like. An external surface may be coated, as in the case of the substrate in the embodiment of Fig. 1 wherein external surface 30 carries high reflector end mirror coating 32 and external surface 36 carries anti-reflection coating 34. A round hole or other aperture can be placed in or on surface 36 or other suitable location to limit beam angles impinging on the filter. Optionally, part 42 of the transparent substrate 28 of the monolithic prism

assembly could be deleted in favor of, e.g., an air gap. Since air has a lower index of refraction, this would yield an advantage in reduced optical distance. It should be recognized that components of the optical device illustrated in Fig. 1 may be spaced from or in abutment with adjacent elements as required by the performance and packaging specifications of a given application.

It can be seen in Fig. 1 that high reflector end mirror 32 on external surface 30 of substrate 28, lies in a transverse plane, that is, in a plane which is substantially normal to the path of travel of collimated light in the external cavity. The Fabry-Perot interference filter 38 is carried at an acute angle to a transverse plane. The angle ∝ (see Figs. 1 and 7) between coating 32 and interference filter 38 at their imaginary intersection point (upward in the plane of the paper as viewed in Figs. 1 and 7) is larger than zero degrees. That is, the filter is not normal or orthogonal to the path of light from the emitter facet. The angle ∝ may be in certain embodiments as large as 45°. Typically, it is 1° to 5°, preferably from 1° to 2°. More generally, the interference filter is positioned at a slight angle between the emitter facet of the laser chip and the high reflector coating defining one end of the external cavity, such that the Fabry-Perot filter is slightly tilted beyond the numerical aperture of the laser chip. Wavelengths which do not fall within the passband of the filter and which are, therefore, not transmitted through the filter, are suppressed. That is, the band pass interference filter suppresses spectral modes which fall outside the passband of the filter primarily by reflecting such out-of-band wavelengths at an angle away from the emitter facet of the laser chip, due to its aforesaid tilt angle.

In operation, light emitted from the anti-reflection coated facet 12 of laser chip 10 is collected and collimated by lens means 24 and directed by it into monolithic prism assembly 26. Light which is in-band of Fabry-Perot interference filter 38 transmits through the filter with low loss along a path represented by arrow 27, while light which is out-of-

band is reflected out of the resonant cavity away from facet 12 along a path represented by arrow 29. Out-of-band wavelengths are reflected by filter 38, therefore, not back to the emitter facet of diode chip 10, but rather along a path whereby it is intentionally lost. The transmitted light, after passing through Fabry-Perot interference filter 38 strikes high reflector end mirror 32 from which it is reflected back toward facet 12 of laser chip 10 along the path of arrow 27, but in reverse direction. The in-band light, therefore passes again through filter 38 as it returns to the emitter facet 12. Advantageously, the monolithic prism assembly 26, including reflector coating 32 and Fabry-Perot interference filter 38, can be assembled into a simple back-to-back miniature prism assembly having a dimension between anti-reflective coating 34 and reflector coating 32 as small as 2 mm or less. The optical device illustrated in Fig. 1 can be packaged sufficiently compactly, therefore, unlike prior known devices, to meet stringent size constraints or limitations of various commercial applications, including certain fiber-optic communications applications, such as DWDM applications.

As noted above, light reflected from high reflector end mirror 32 passes back again through Fabry-Perot interference filter 38, thereby further removing unwanted out-of-band light while transmitting in-band light. The transmitted in-band light passes again through lens means 24 whereby it is reinjected into the laser diode 10, amplified and directed to the output facet 14. As indicated above, output facet 14 carries partially reflective output coupler mirror coating 16, such that a portion of the light striking coating 16 is reflected back into the laser chip to continue the oscillation function, and the remainder is transmitted out of the laser to fiber-optic pigtail 20. Second collimater 18 can be used to collimate the light from output facet 14 into fiber-optic pigtail 20, preferably having anti-reflection coatings 48 and 50 on its exterior surfaces in the path of travel of the light. Typically, an anti-reflective coating 52 also will be provided at the input surface of fiber-optic pigtail 20.

Similarly, surface 25 of collimating means 24 carries anti-reflection coating 35. Generally, it will also be preferred to provide a very slight angle to surfaces carrying anti-reflection coatings, such as coatings 16, 22, 34, 35, 48, 50. By angling or tilting these surfaces away from a transverse plane, such that they are not precisely normal to the path of travel of the light, undesirable back reflection due to imperfect anti-reflection is reduced or eliminated.

The overall length of the external cavity of the laser is equal to the length of the laser diode itself, plus the length of the in-cavity collimating lens 24, plus the focus distance between the laser end facet 12 and the in-cavity collimating lens, plus the length of the monolithic prism assembly. Those skilled in the art will recognize, however, that the total optical cavity length is the product of each such individual length component multiplied by the average refractive index of that component. The length of the laser cavity defines the wavelength spacing of the longitudinal modes that the laser can support. To provide a single mode output in accordance with certain preferred embodiments, the bandwidth of the Fabry-Perot interference filter of the monolithic prism assembly is made narrower than the adjacent spectral mode spacing. In those embodiments in which the Fabry-Perot interference filter is wider than the mode spacing, more than one mode may be emitted, which may be disadvantageous for certain long haul telecommunications applications, but which has usefulness in other applications. The spectral mode spacing, referred to as Delta-Lambda can be calculated in accordance with the formula:

$$\text{Delta-Lambda} = \text{Lambda}^2 / [2 \times \text{cavity length} \times \text{refractive index}]$$

In a preferred embodiment in accordance with Fig. 1, the components have the size and optical properties shown in Table 1 below:

TABLE 1

Component	Typical Length	Av. N.	Product
Laser Chip	0.5 mm	3.6	1.8
Gradient index		1.0 mm	1.5
1.5			
Focus distance	0.2 mm	1.0	0.2
Filter/mirror	2.0 mm	1.5	3.0
Total	3.7		6.5

Using the formula given above and the numerical values of Table 1, where "Av. N." is the spacing of possible longitudinal lasing modes for the preferred embodiment in accordance with Fig. 1 Delta-Lambda will be approximately 0.17 nm. For single mode operation, the Fabry-Perot interference filter of the monolithic prism assembly is preferably a bandpass filter having bandwidth less than twice such value, that is, less than 0.34 nm. Preferably, the filter has a bandwidth of less than 0.3 nm. As used here, the bandwidth of the filter is its 3dB bandwidth that is, the width in nanometers over which at least 50% of total received emissions are transmitted through the filter. Employing a multi-cavity Fabry-Perot interference filter, specifically, a two-cavity ultra-narrow bandpass filter centered at 1550 nm with bandwidth of 0.25 nm, in accordance with preferred embodiments discussed further below, a spectral mode at 1550 nm is transmitted while other modes will be rejected. In particular, in each pass through the filter the nearest spectral modes at 1550.17 nm and 1548.83 nm will be rejected by approximately 8 dB. Thus, effectively total rejection of these adjacent spectral modes can be achieved, as the light must travel twice through the Fabry-Perot interference filter, once passing from the laser chip to the high reflector end mirror 32, and a second time reflected back from the end mirror 32 to the laser chip. Spectral modes farther from the 1550 nm transmittance mode are rejected in even greater degree.

In this regard, the effect of using multiple-cavity interference filters is illustrated in the graph of Fig. 6. It can be seen in Fig. 6 that the transmittance properties at 1550 nm are excellent for one-cavity, two-cavity and three-cavity filters. The spectral skirts of the two-cavity and three-cavity filters have increasingly greater slope, along with a wider transmission zone, as compared to a single cavity filter. That is, out-of-band spectral modes are reflected in greater degree by a two-cavity filter than a one-cavity filter, and the effect is substantially increased for a three-cavity filter over a two-cavity filter. Both of these effects are advantageous to the performance of external cavity lasers in accordance with the preferred embodiments discussed here, providing advantages over prior known filtering devices, such as etalons and diffraction gratings. Thus, the optical performance of an external cavity diode laser as disclosed here is achieved by controlling the Fabry-Perot interference filter of the monolithic prism assembly. As discussed further below, excellent techniques are available for reproducibly producing Fabry-Perot interference filters with bulk density near unity to prevent water absorption induced filter shifting, etc. This is especially true in those preferred embodiments wherein the Fabry-Perot interference filter is provided on an internal surface of the monolithic prism assembly.

It can be seen that the optical device of Fig. 2 has aspects in common with Fig. 1, and it will be understood to function in correspondingly similar fashion. The reference numbers of Fig. 1 are used for common elements or features in Fig. 2. Output coupler mirror coating 16 of the embodiment of Fig. 1 is replaced by high reflector end mirror coating 17 in the embodiment of Fig. 2. End mirror 17 defines the right-hand side (as viewed in Fig. 2) of the resonant cavity. Additionally, high reflector end mirror 32 in the embodiment of Fig. 1 is replaced in the embodiment of Fig. 2 with optical coupler coating 33. Light is emitted through coating 33 to optical receiver device 56, for example, a fiber optic pig tail, light sensor, etc. More specifically, light emitted through coating 33 passes

to optical isolator 54 and then to gradient index lens 55 before reaching pigtail 56. Anti-reflective coatings 57 are provided in accordance with known techniques. In certain applications the embodiment of Fig. 2 advantageously avoids amplifying "noise" as light passes back through the laser diode. Those skilled in the art will recognize that an optical coupler such as coating 33, specifically, a coating in the nature of a beam splitter, could be used in the embodiment of Fig. 1 in place of high reflector end mirror 32 to provide a signal to an optical receiver device. The optical receiver device may comprise, for example, a diode sensor for a power feedback loop or simply an output signal carrying optical fiber, etc.

The thin film Fabry-Perot interference filter of the monolithic prism assembly used in the optical devices disclosed here can be produced in accordance with commercially known techniques, whose applicability will be readily apparent in view of the present disclosure. In particular, high-quality interference filters comprising stacked layers of metal oxide materials, such as niobia and silica, can be produced by commercially known plasma deposition techniques, such as ion assisted electron beam evaporation, ion beam sputtering, and reactive magnetron sputtering, for example, as disclosed in U.S. patent No. 4,851,095 to Scobey et al. Such coating methods can produce interference cavity filters formed of stacked dielectric optical coatings which are advantageously dense and stable, with low film scatter and low absorption, as well as low sensitivity to temperature changes and ambient humidity. The spectral profile of such coatings is suitable to meet stringent application specifications. In particular, multi-cavity narrow bandpass filters can be produced using such techniques, which are transparent to a wavelength range separated from an adjacent wavelength range (e.g., from the wavelength range of an adjacent channel in a dense wavelength division multiplexing fiber optic system) by as little as two nanometers or less. One suitable deposition technique is low pressure magnetron spattering in which the

vacuum chamber of a magnetron sputtering system which can be otherwise conventional, is equipped with high speed vacuum pumping. A gas manifold around the magnetron and target material confines the inert working gas, typically argon, in the vicinity of the magnetron. As the gas diffuses and expands from the area of the magnetron, the unusually high pumping speed vacuum removes the expanding gas from the chamber at a high speed. The inert gas pressure in the chamber, preferably in the range of 5×10^{-5} Torr to 1.5×10^{-4} Torr, is then a function of the pumping speed of the vacuum pump and the confinement efficiency of the magnetron baffle. Reactive gas enters the chamber through an ion gun which ionizes the gas and directs it toward the substrate. This has the effect of reducing the amount of gas required to provide the film with proper stoichiometry as well as reducing the reactive gas at the magnetron. Throw distance of 16 inch and longer can be achieved.

As noted above, the filter preferably comprises a multi-cavity coating in which two dielectric thin film stacks which by themselves form a reflector for the unwanted wavelengths are separated by a cavity layer. This structure is then repeated one or more times to produce the aforesaid multi-cavity filters with enhanced blocking and improved in-band transmission flatness. The net effect is to produce a narrowband transmissive filter where in-band light is transmitted and out-of-band light is reflected. In preferred three-cavity embodiments produced by the deposition techniques mentioned above, with dense, stable metal oxide film stacks, excellent thermal stability has been achieved, for example, 0.004 nm per degree centigrade or better at 1550 nanometers, and ultra-narrow band widths separated by as little as 2 nm or even as little as 1 nm.

In accordance with the above mentioned preferred embodiments, the interference filter typically is formed of two materials, the first being a high refractive index material such as niobium pentoxide, titanium dioxide, tantalum pentoxide and/or mixtures thereof, for example, mixtures of niobia and titania, etc. At 1.5 microns wavelength, the refractive

index for these materials is roughly 2.1 to 2.3. The low refractive index material is typically silica, having a refractive index of about 1.43. An interference filter has an "optical thickness" which is the numerical product of its physical thickness times its refractive index. The optical thickness of the Fabry-Perot interference filter used in the monolithic prism assembly of the optical devices disclosed here varies, of course, with the physical thickness of the filter and with the refractive index of the material selected. It will be well within the ability of those skilled in the art, in view of this disclosure, to select suitable materials and film thicknesses to achieve spectral transmittance properties suitable to meet the requirements of a given application.

The monolithic prism assembly comprising a thin film Fabry-Perot interference filter in the optical devices disclosed here has significant advantages over prior known devices used for such optical devices. Especially when produced with durable materials to form dense layers of near unity packing density, the interference filter of the monolithic prism assembly is highly stable over time and with respect to humidity and other ambient conditions. Furthermore, a large number of optical substrate blocks can be coated simultaneously with the interference filters in a single coating run, thereby substantially reducing manufacturing costs. They are readily manufactured comprising multiple cavities coherently coupled using quarter wave thickness layers in accordance with known techniques, yielding increased slope of the spectral skirts along with a wider transmission zone. As discussed above, all of these effects, plus the miniature size in which the monolithic prism assembly can be readily fabricated, offer significant advantages over other types of filtering devices, such as etalons and diffraction gratings. Moreover, the stability of the interference filter is enhanced, since it is formed on an optical substrate, especially when carried on an internal surface of the monolithic prism assembly, as discussed above. Such interference filters can be produced in extremely small sizes, for example, less than

0.5 mm thick and only a few millimeters in diameter. As such, they can be readily packaged into tiny, relatively low-cost laser devices. They can be readily manufactured using commercially available techniques to transmit an intended or specified wavelength within plus or minus 0.1 nm, with extremely narrow bandwidths of, for example, 0.3 nm or less. As noted above, transmission of the in-band wavelength range can be extremely high.

Preferred film stack structures for the multi-cavity interference filter 38 in the preferred embodiments of the FL laser illustrated in Figs. 1 and 2 are illustrated in Figs. 3 - 5. Preferably, the thickness of each alternating layer (for example, of niobium pentoxide and silicon dioxide), as well as the total thickness of the film stack, is precisely controlled, e.g. within 0.01% or 0.2 nm over several square inches of area. In addition, film stacks deposited with very low film absorption and scatter and with packing density near unity have low water-induced filter shifting. Such ultra-narrow, multi-cavity bandpass filters have excellent performance characteristics, including: temperature and environmental stability; narrow bandwidth; high transmittance of the desired optical signal and high reflectance of other wavelengths; steep edges, that is, highly selective transmissivity (particularly in designs employing three cavities or more); and relatively low cost and simple construction. A three-cavity filter is shown in Fig. 3, sandwiched between parts 42 and 44 of a transparent optical substrate. (See Figs. 1 and 2.) The first cavity assembly 85 is immediately adjacent substrate part 44. A second cavity assembly 86 immediately overlies the first cavity and a third cavity assembly 87 immediately overlies the second cavity assembly and forms a surface-to-surface interface with substrate part 42. In Fig. 4 the structure of the "first cavity" 85 is further illustrated. A sequence of stacked films, preferably about 5 to 15 films of alternating high and low refractive index materials, are deposited to form a first reflector. Preferably, the first film immediately adjacent the substrate surface is a layer of high index material, followed by a layer of low index material.

etc. Each of the high index layers 90 is an odd integer of quarter wavelengths optical thickness (QWOT) preferably one or three quarter wavelengths or other odd number of QWOTs. The low refractive index layers 92 which are interleaved with the high refractive index layers 90 are similarly one quarter wavelength optical thickness or other odd number of QWOTs in thickness. There may be, for example, about six sets of high and low refractive index layers forming the bottom-most dielectric reflector 94. Cavity spacer 96, although shown schematically as a single layer, typically comprises one to four alternating films of high and low index materials, wherein each of the films is an even number of QWOTs in thickness, that is, an integral number of half wavelengths optical thickness. The second dielectric reflector 98 preferably is substantially identical to dielectric reflector 94 described above. The second and third cavities are deposited, in turn, immediately upon the first cavity and preferably are substantially identical in form.

One alternative film stack is illustrated in Fig. 6, wherein the upper and lower reflectors 94, 98 are as described above for the embodiment of Figs. 4 and 5. The cavity spacer 97 is shown to be formed of four films, two high index films 97a alternating with two low index films 97b. Each film is 2 QWOTs thick or one half wavelength. Various other alternative suitable film stack structures are possible, and will be apparent to those skilled in the art in view of this disclosure.

In accordance with a further preferred aspect, the Fabry-Perot interference filter of the monolithic prism assembly of the optical devices disclosed here may be further temperature stabilized or made otherwise tunable through the use of tilt adjustment means. That is, means can be provided, most preferably associated with the mounting means for the monolithic prism assembly, for altering the tilt angle of the Fabry-Perot interference filter, either independently or not of the presentation angle of any other coating carried by the monolithic prism assembly. In typical preferred embodiments, the angle of the filter to the

collimated light is increased as temperature increases, and correspondingly decreased as the temperature of the filter drops. In addition, similar techniques can be used to tune the wavelengths by adjusting the tilt angle of the filter.

The alternative preferred embodiment of an FL laser schematically illustrated in Fig. 7 will be understood from the following description to operate in accordance with the principles discussed above. A first diode laser 58 carries a high reflector end mirror 60 at a first emitter facet 62, and anti-reflection coating 64 at the opposite emitter facet 65 at its interface with collimating means 66. A second diode laser 68 carries optical coupling coating 70 at emitter facet 72, such that a resonant cavity is established between coating 70 and coating 60. Light which passes through optical coupler coating 70 is received by fiber optic pigtail 73 after passing through collimating means 74. Second emitter facet 76 of the second diode laser 68 carries anti-reflection coating 77 through which light is passed to collimating means 78. Positioned between collimating means 78 associated with the second emitter facet 76 of diode laser 68 and the collimating means 66 associated with first diode laser 58 is a monolithic prism assembly 79 carrying a thin film Fabry-Perot narrowband filter 80 on internal surface 81. Additional anti-reflection coatings 82 are used at the various surfaces of elements of the optical device. It will be recognized that high reflector end mirror 60 could be replaced by an optical coupling coating, such that light could be emitted from the laser device to a fiber optic pigtail, diode sensor of a power feedback loop, etc. Various components of Fig. 7 shown spaced apart can advantageously be butt coupled to reduce the overall size of the device and its optical length.

A dense channel wavelength division multiplexing device is illustrated in Fig. 8, employing an FL laser as disclosed above at each of eight separate ports or channels on an optical block 100. This multiplexing device has the ability to multiplex individual, separate wavelength signals into a common fiber optic carrier line and/or to demultiplex such signals.

Typical specifications for an optical multiplexing device in accordance with the preferred embodiment illustrated in Fig. 8 include those provided in Table 2.

TABLE 2

Number of Channels	8
Channel wavelength	1544-1560
Channel spacing	2 nm ± 0.2 nm
Minimum Isolation	20 dB to 35 dB
Insertion loss (total)	less than 6 dB
Fiber type	single mode, 1 meter pigtail
Operating temperature range	-20°C to +50°C

The optical multiplexing device of Fig. 8 meeting the specifications of Table 2, in addition to optical block 100 which, preferably, is a stable glass substrate, is seen to include means for receiving collimated light, such as a fiber optic gradient index lens collimator 112 or the like, receives highly collimated light 114 from optical port 118 of the optical block at a slight angle through a hole or facet in surface 116 of the optical block. In accordance with one preferred embodiment, the optical block has a thickness "a" of 5 mm, a length "b" of 14.1 mm or more, and a refractive index of about 1.5. The collimated light preferably has a divergence of not more than about 0.15° and the tilt angle "c" at which the collimated light exits the optical block is about 15°. Multi-wavelength light bounces within the optical block between the high reflector coating 134 and opposite surface 120. A channel (or multiple channels) are added (or removed) at each (or every other, etc.) bounce by a reflective filter which transmits a next wavelength increment. Alternative to such series of filters, a graded wavelength, preferably all-dielectric, narrowband bandpass filter 122 is carried on surface 120 of the optical block. Such filter can be made in accordance with the teachings of co-pending, commonly owned U.S. patent application Serial No. 08/490,829, filed June 15, 1995 and entitled "Optical Multiplexing Device," the disclosure of which is incorporated herein by reference. Specifically, filter 122 in such embodiments is a

continuous, variable thickness, multi-cavity interference filter, and, most preferably, is a continuous linearly variable filter. Such filter 122 is transparent at port 124 to a sub-range of the wavelengths included in the collimated light 114. Specifically, light 126 passes through port 124 of the optical block from a collimating lens means 128 associated with a first signal channel. The optical signal passed by port 124 is generated by an external cavity semiconductor diode laser 129 in accordance with any of the preferred embodiments discussed above, meeting stringent spectral performance characteristics in accordance with Table 2, for a first channel of the multiplexing device.

The continuous filter 122 at port 124 is reflective of wavelengths which are not "in-band" of the filter at that location. Light 132 is reflected between filter 122 on surface 120 of the optical block and high reflector film or coating 134 on surface 116. High reflector film 134 does not cover optical port 118, so as to avoid interfering with the passage of light 114. Thus, light 132 is reflected by reflector film 134 to strike surface 120 of the optical block at port 124, where it is reflected to pass through port 118. At the location of port 136 next adjacent to port 124, the continuous, variable thickness, multi-cavity interference filter 122 is transparent to a different wavelength or sub-range of wavelengths than it is at port 124. For dense channel wavelength division multiplexing applications, the wavelength separation between each of the multiple ports linearly spaced along surface 120 of the optical block is preferably about 2 nm or less. Thus, at port 136 an optical signal corresponding to a second channel is transmitted through the filter 122 from a collimating lens 138, generated by external cavity semiconductor diode laser 139 in accordance with the preferred embodiments above. As at the first port 124, the interference filter 122 at port 136 reflects light which is not in-band at that location. Thus, the portion 142 of the light 114 which first entered the optical block prior to this point (i.e., light having wavelengths of others of the channels, originating at laser diode devices 149, 159, 169, 179, 189 or 199)

is reflected on toward port 118 from port 136. In similar fashion, the reflected wavelengths at earlier points in the optical block cascade in a zigzag or "multiple-bounce" path in the optical block, with the optical signal for each individual channel being added at successive bounces at surface 120 of the optical block.

It is a technologically and commercially significant advantage of preferred embodiments of the devices disclosed here, that multiple channels can be so tightly spaced in a narrow wavelength range, with reliable and precise generation of desired wavelengths sub-ranges by reliable and commercially feasible external cavity diode laser devices. With FL lasers, such DWDM multiplexing devices can now be mass produced with suitable wavelength control and consistently reproducible spectral performance characteristics such that fiber-optic DWDM multiplexed systems are rendered commercially feasible.

It will be apparent from the above disclosure of the invention and detailed discussion of certain preferred embodiments that various additions and modifications can be made to the embodiments disclosed without departing from the true scope and spirit of the invention. All such modifications and additions are intended to be covered by the following claims.

I Claim:

1. An external cavity laser comprising, in combination, a semiconductor optical amplifier optically coupled to an external resonant cavity, and a monolithic prism assembly in the external resonant cavity comprising a transparent substrate having a thin film Fabry-Perot narrowband interference filter at an acute angle to a transverse plane of the external resonant cavity.

2. The external cavity laser in accordance with claim 1 wherein the acute angle of the thin film Fabry-Perot interference filter of the monolithic prism assembly to a transverse plane of the external resonant cavity is greater than zero degrees and less than 45°.

3. The external cavity laser in accordance with claim 1 wherein the thin film Fabry-Perot interference filter has a bandwidth of less than 0.3 nm.

4. The external cavity laser in accordance with claim 1 wherein the thin film Fabry-Perot interference filter comprises multiple thin film reflector layers sandwiching between them at least one thin film cavity layer.

5. The external cavity laser in accordance with claim 4 wherein each cavity layer is formed of one to four dielectric films of alternating high and low refractive index, each having an optical thickness equal to an integral number of half wavelengths, and the reflector layers each is formed of two to twelve dielectric films of alternating high and low refractive index, each having an optical thickness equal to an odd number of quarter wavelengths.

6. The external cavity laser in accordance with claim 1 wherein the thin film Fabry-Perot interference filter is a multi-cavity narrowband filter.

7. The external cavity laser in accordance with claim 6 wherein the Fabry-Perot interference filter has a bandwidth of less than 0.3 nm.

8. The external cavity laser in accordance with claim 7 wherein the external resonant cavity has an overall length of less than 5 nm.

9. The external cavity laser in accordance with claim 1 wherein the semiconductor optical amplifier comprises a direct bandgap semiconductor optical emitter.

10. An external cavity laser comprising, in combination, a semiconductor optical amplifier optically coupled to an external resonant cavity, and a monolithic prism assembly in the external resonant cavity comprising a transparent substrate having a transverse first surface and a Fabry-Perot interference filter on a second surface at an acute angle to the first surface, the Fabry-Perot interference filter comprising multiple thin film reflector layers sandwiching between them at least one thin film cavity layer.

11. The external cavity laser in accordance with claim 1 wherein the acute angle is from 1° to 5°.

12. An external cavity laser comprising, in combination. a semiconductor optical amplifier optically coupled to an external resonant cavity, and a monolithic prism assembly

in the external resonant cavity comprising a transparent substrate carrying a Fabry-Perot interference filter at an acute angle to a transverse plane of the external resonant cavity, the Fabry-Perot interference filter comprising at least one cavity layer formed of half wavelength optical thickness dielectric films sandwiched between reflector layers each formed of quarter wavelength optical thickness dielectric films.

13. The external cavity laser in accordance with claim 12 wherein the Fabry-Perot interference filter is a three-cavity filter.

14. A monolithic prism assembly comprising a transparent optical substrate carrying a reflective coating on a first surface of the optical substrate in a first plane and a thin film Fabry-Perot narrowband interference filter on a second surface of the optical substrate in a second plane spaced from and at an acute angle to the first plane.

15. The monolithic prism assembly of claim 14 wherein the Fabry-Perot interference filter is a multi-cavity narrowband filter.

16. The monolithic prism assembly of claim 15 wherein the Fabry-Perot interference filter has a bandwidth of less than 0.2 nm.

17. The monolithic prism assembly of claim 14 wherein the reflective coating is a high- reflective coating on an external surface of the substrate, and the Fabry-Perot interference filter is on an internal surface of the substrate.

18. The monolithic prism assembly of claim 14 further comprising a second reflective coating on a third surface of the optical substrate in a third plane which is parallel to the first plane and on an opposite side of the second plane.

19. An optical device comprising, in combination:

an external cavity laser comprising a semiconductor diode laser having an anti-reflection coating on a first emitter facet optically coupled to an external resonant cavity,

a monolithic prism assembly in the external resonant cavity comprising a transparent optical substrate carrying a thin film Fabry-Perot narrowband interference filter at an acute angle to a transverse plane of the external resonant cavity, and

collimating means for focusing light between the emitter facet and the Fabry-Perot interference filter.

20. The optical device in accordance with claim 19 wherein the diode laser is an edge emitting diode laser.

21. The optical device in accordance with claim 20 further comprising an output coupler reflective coating on a second facet of the diode laser.

22. The optical device in accordance with claim 21 wherein the monolithic prism assembly further comprises a reflective coating on a transverse first surface of the transparent optical substrate at one end of the external resonant cavity, and the thin film Fabry-Perot narrowband interference filter is on a second surface of the optical substrate at an acute angle to the first surface.

23. The optical device in accordance with claim 22 wherein the thin film Fabry-Perot narrowband interference filter is a multi-cavity filter.

24. The optical device in accordance with claim 23 wherein the Fabry-Perot interference filter has a bandwidth of less than 0.3 nm.

25. The optical device in accordance with claim 24 wherein the external resonant cavity has an overall length of less than 5 mm.

26. The optical device in accordance with claim 22 wherein the reflective coating is a high- reflective coating on an external surface of the substrate, and the Fabry-Perot interference filter is on an internal surface of the substrate.

27. An optical device comprising, in combination, an external cavity semiconductor diode laser, an anti-reflection coating on a first emitter facet of the diode laser optically coupled to an external resonant cavity, an output coupler reflective coating on a second emitter facet of the diode laser, a monolithic prism assembly in the external resonant cavity comprising a transparent optical substrate carrying a cavity-reflectiv coating at one end of the external resonant cavity and a thin film Fabry-Perot interference filter within the external resonant cavity between the reflective coating and the first emitter facet at an acute angle to the reflective coating, the thin film Fabry-Perot interference filter comprising multiple thin film reflectors sandwiching between them at least one thin film cavity layer.

28. The optical device in accordance with claim 27 wherein the cavity reflective coating is a high-reflective coating.

29. The optical device in accordance with claim 27 wherein the cavity-reflective coating is partially transparent and optically couples the diode laser to an output element.

30. The optical device in accordance with claim 29 wherein the output element is a diode sensor of a power feedback loop.

31. The optical device in accordance with claim 27 wherein the output coupler reflective coating is optically coupled through a second collimating means to a fiber-optic pigtail.

32. An optical device comprising, in combination:

an external cavity semiconductor diode laser comprising first and second edge emitting lasers at opposite ends of a common external resonant cavity, the first edge emitting laser having a first reflective coating on a first facet defining a first end of the external resonant cavity, and the second edge emitting laser having an output coupler reflective coating on a second facet defining a second end of the external resonant cavity and optically coupling the diode laser to an output element;

a monolithic prism assembly in the external resonant cavity between the first and second edge emitting lasers, comprising a transparent optical substrate carrying a thin film Fabry-Perot interference filter having at lest one thin film cavity sandwiched between thin film reflectors; and

collimating means focusing light between the first and second edge emitting lasers.

33. The optical device in accordance with claim 32 wherein the monolithic prism assembly has first and second anti-reflection coatings on parallel external surfaces, the thin film Fabry-Perot interference filter being on an internal surface of the monolithic prism assembly between the first and second anti-reflection coatings.

34. The optical device in accordance with claim 32 wherein the output element is a second collimating means optically coupled to a fiber-optic pigtail.

35. The optical device in accordance with claim 32 wherein the first reflective coating is a high-reflective coating.

36. The optical device in accordance with claim 32 wherein the first reflective coating is partially transparent and optically couples the diode laser to a second output element.

37. A dense wavelength division multiplexing fiber-optic communication system comprising, in combination, a semiconductor diode laser having a monolithic prism assembly in an external resonant cavity of overall length less than 5 mm, the monolithic prism assembly comprising a transparent optical substrate carrying on an internal surface a multi-cavity thin film Fabry-Perot interference filter having a bandwidth of less than 0.3 nm, angled to reflect out-of-band wavelengths away from the diode laser and comprising multiple thin film reflectors sandwiching between them at least one thin film cavity.

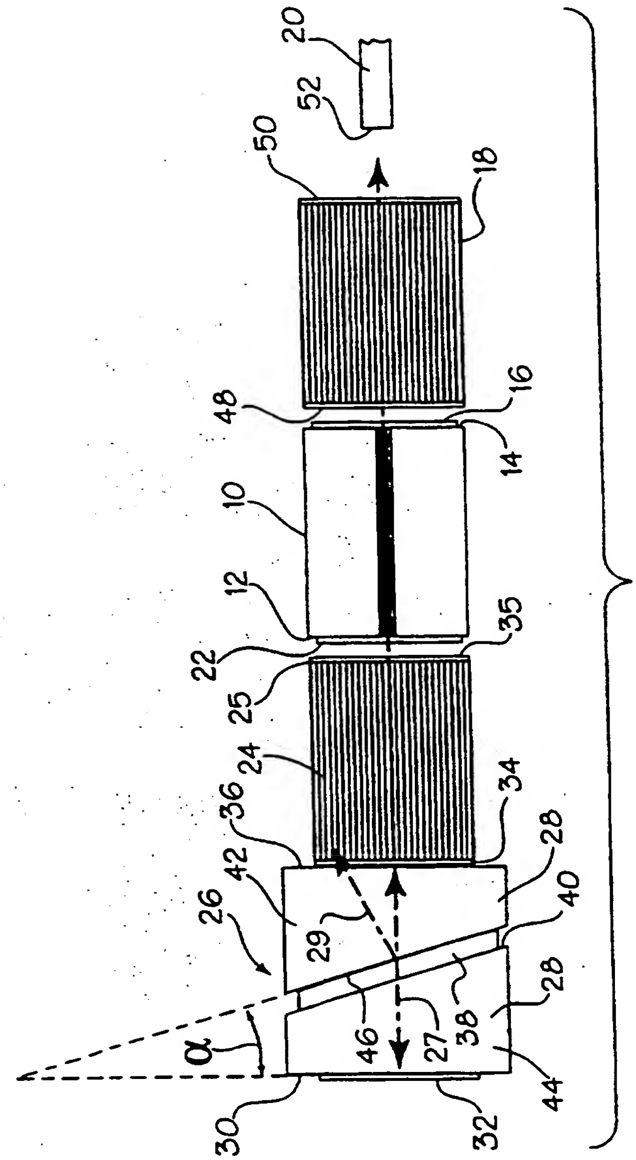
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Fig. 1

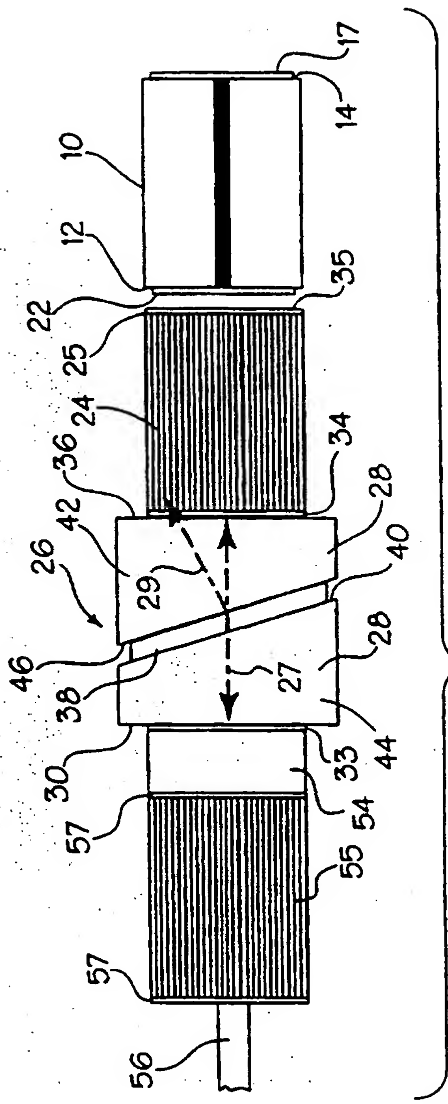
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Fig. 2

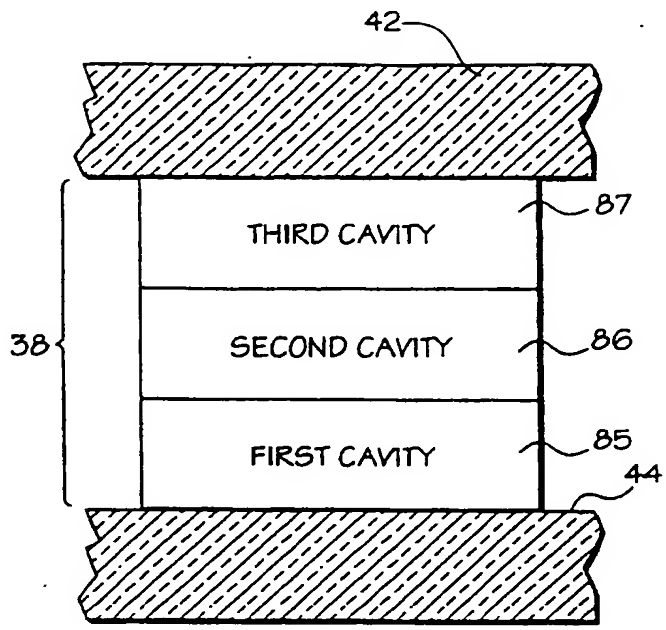
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Fig. 3

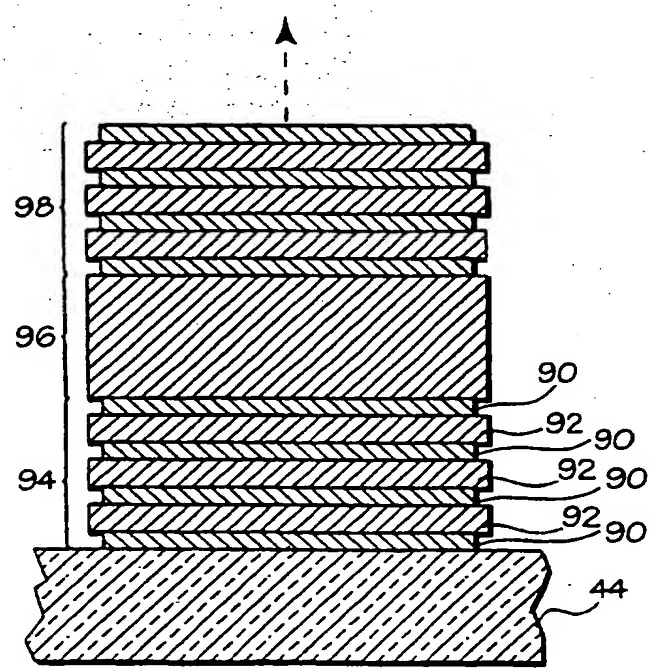
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Fig. 4

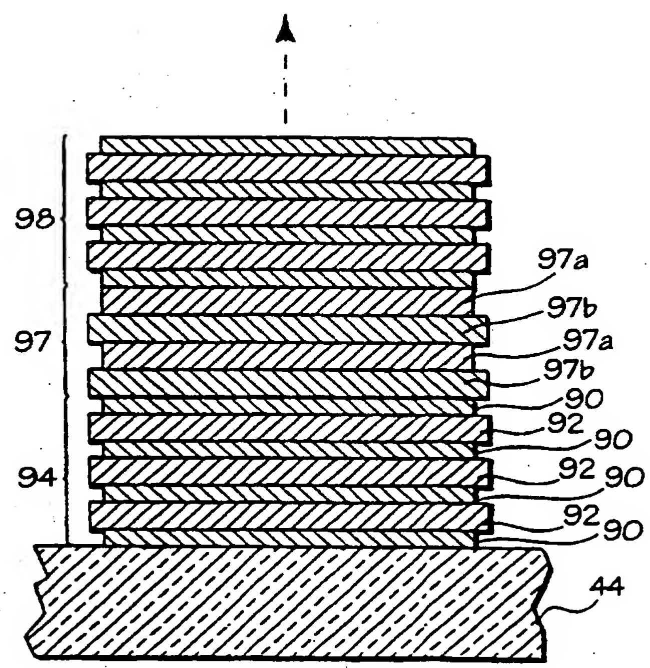
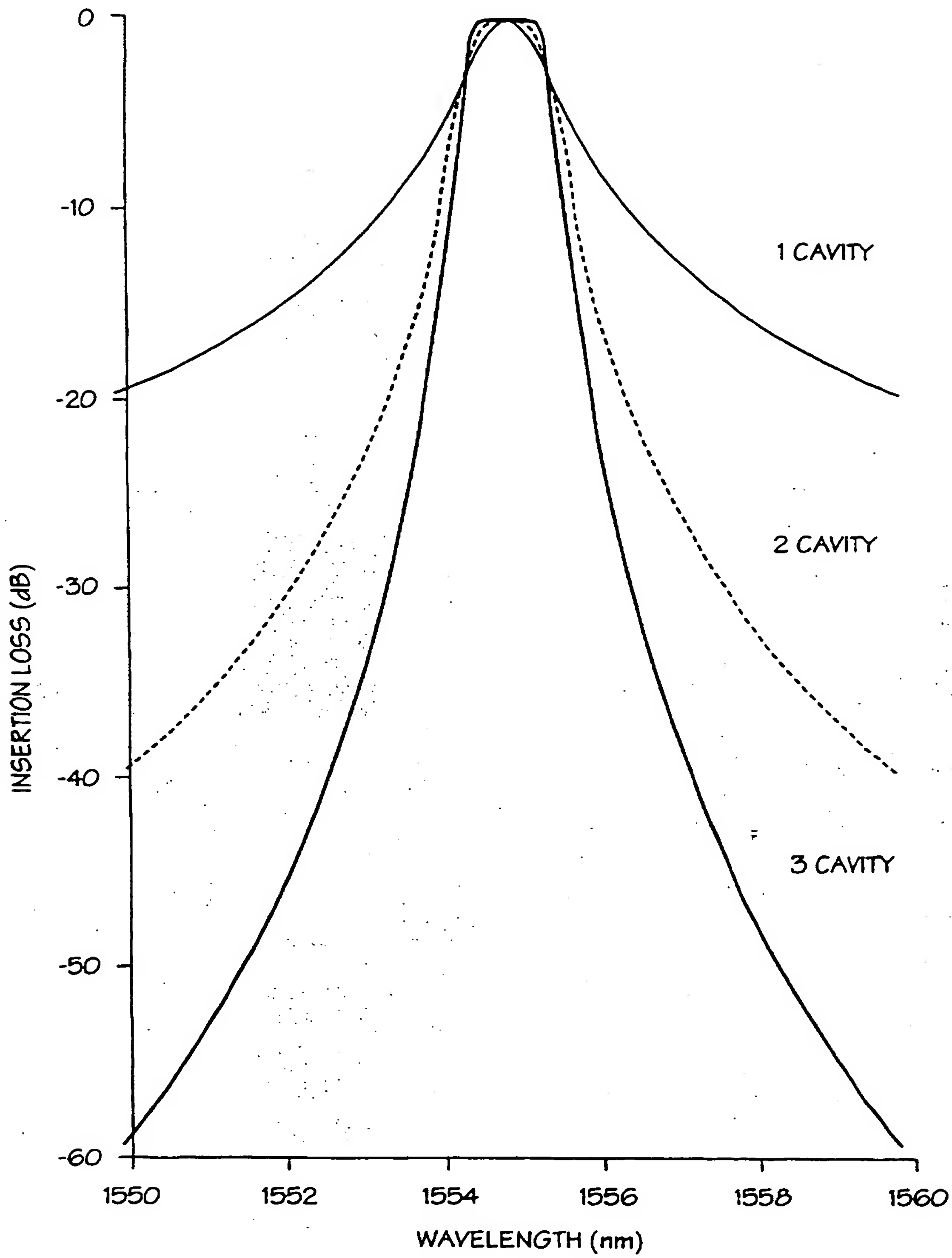


Fig. 5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INSERTION LOSS (dB)
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WAVELENGTH (nm)
1 CAVITY
2 CAVITY
3 CAVITY

Fig. 6

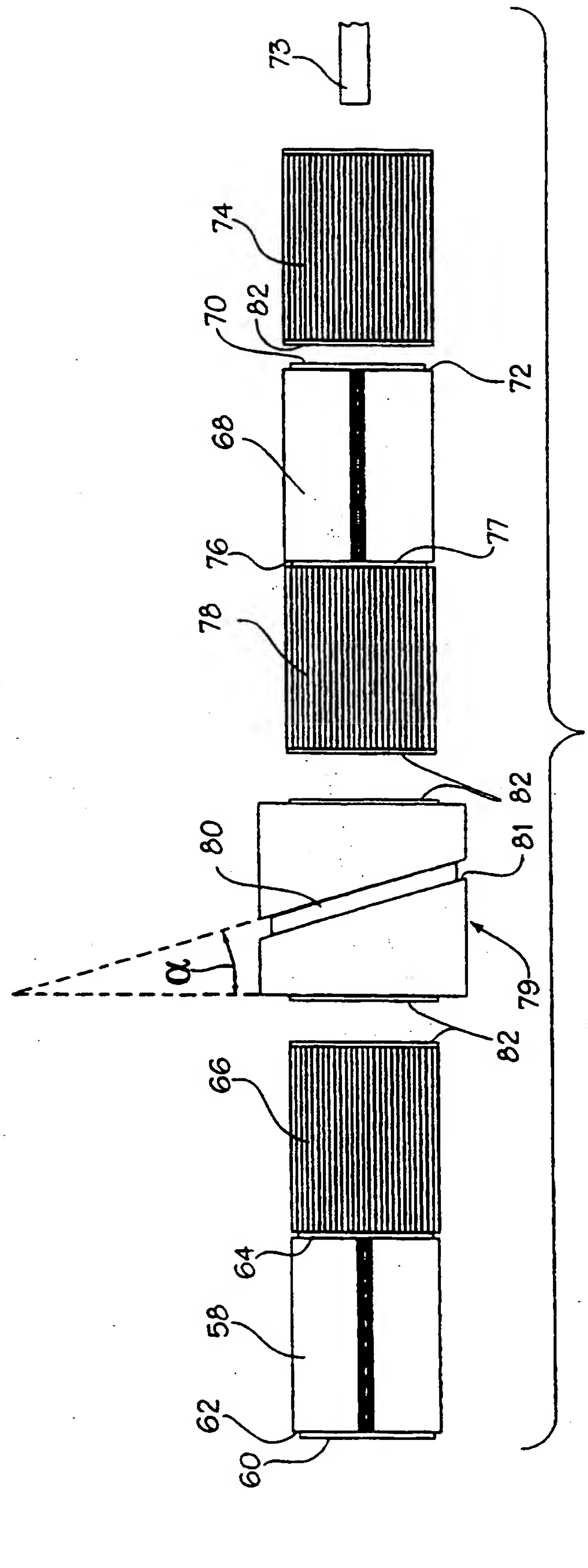

Fig. 7

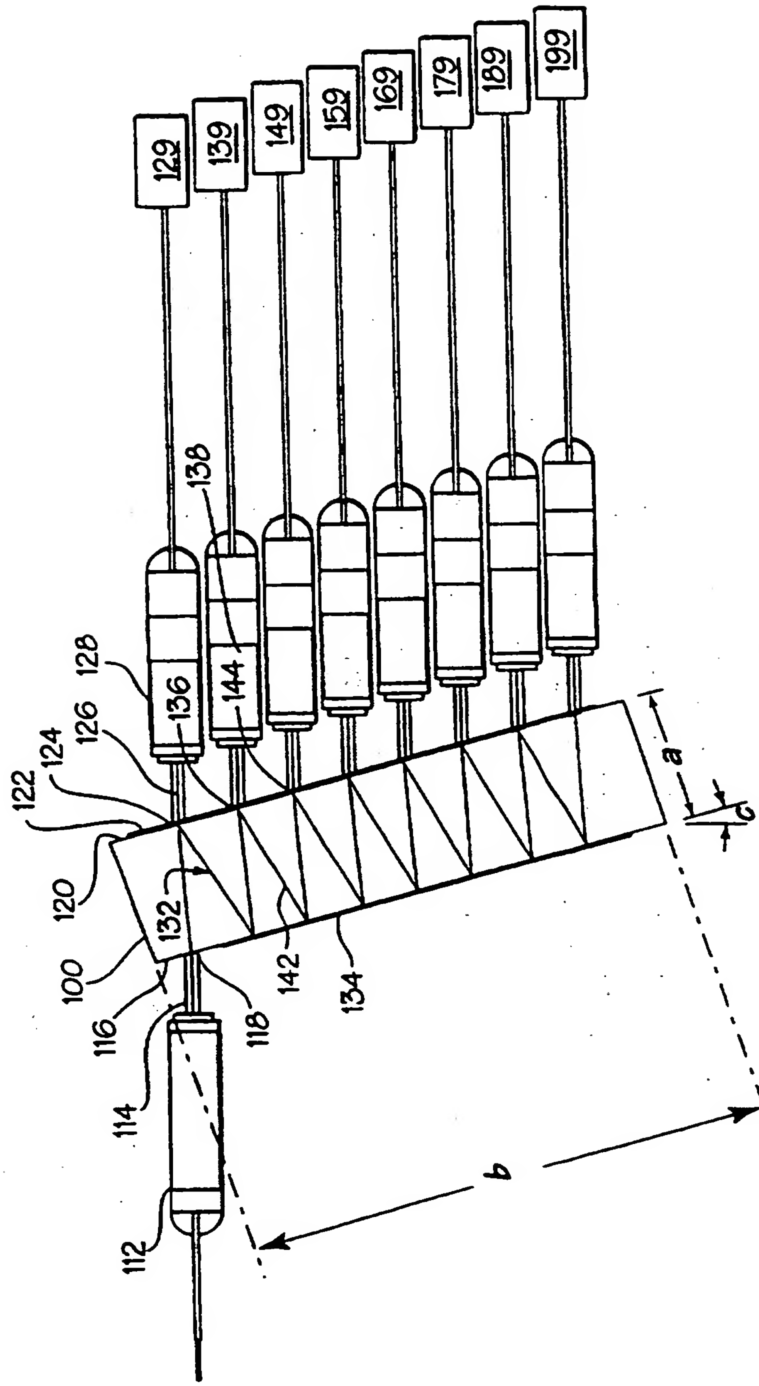
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Fig. 8

INTERNATIONAL SEARCH REPORT

Inte   onal Application No
PCT/US 97/02190

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/085 H01S3/098 G02B5/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 262 435 A (SIEMENS AG) 6 April 1988 see abstract; figure 1 ---	1,2,10, 12,19, 20,27, 32,37
A	US 4 504 950 A (AUYEUNG JOHN C) 12 March 1985 see the whole document ---	1,2,10, 12,19, 20,27
A	PATENT ABSTRACTS OF JAPAN vol. 015, no. 487 (P-1286), 10 December 1991 & JP 03 209638 A (FUJITSU LTD), 12 September 1991, see abstract ---	1,10,12, 19,27,32
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
5 June 1997	18.06.97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Claessen, L

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/02190

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 1, no. 7, July 1989, pages 159-161, XP000053582 KAHN J M ET AL: "HIGH-STABILITY 1.5 M EXTERNAL-CAVITY SEMICONDUCTOR LASERS FOR PHASE-LOCK APPLICATIONS" see the whole document ---	1,10,12, 19,27, 32,37
A	ELECTRONICS & COMMUNICATIONS IN JAPAN, PART I - COMMUNICATIONS, vol. 61, no. 9, September 1978, NEW YORK US, pages 81-86, XP002032441 H. MATSUZAWA ET AL: "wavelength tuning of a dye laser using a prism coated with dielectric interference filter" see the whole document ---	1,10,12, 19,27, 32,37
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